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GRBs as probes of the high-z universe

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Abstract. Here I will discuss the possibility of using high-z Gamma Ray Bursts (GRBs) to probe the primordial universe.

Key words. Cosmology: intergalactic medium – Galaxy: star formation rate – Stars: gamma ray bursts

1. Introduction

As of today there are three Gamma Ray Bursts (GRBs) with spectroscopically identified redshift larger than 6, the record being held by GRB 090423, with a redshift of 8.1 (Salvaterra et al. 2009) or 8.26 (Tanvir et al. 2009). This GRB has also held the record for the highest redshift object, detained now by a galaxy at 8.6 (Lehnert et al. 2010). It is intriguing that this extreme GRB does not exhibit any characteristics sensibly different to its lower-z counterparts. In fact, its rest-frame γ-ray and X-ray light curves (Fig. 1) show no distinguishing feature, nor do other quantities such as energy, circumburst medium and jet opening angle (Fig. 2), in particular because several GRBs at lower-z have been associated with an isotropic blast wave kinetic energy in excess of 10^{52} ergs (e.g. Chandra et al. 2010). This suggests that the physical mechanism that caused the GRB and its interaction with the circumburst medium are similar to the lower-z counterparts.

Despite this normality, these kind of sources are extremely important because they can be used to probe the high-z universe, in analogy to what is done with QSOs and galaxies. In principle, they are even better probes for a number of reasons, among which: *(i)* since the GRBs progenitors are believed to be stellar, they likely originate in the most common star forming galaxies at any given z, rather than in the most massive galaxies as in the case of bright QSOs and thus they are less biased and affected by local ionization effects and strong clustering; *(ii)* for the same reason, the intrinsic luminosity of the engine should not depend on the mass of the host, differently from QSOs and galaxies, whose mass is expected to be smaller at higher z, and thus GRBs should be increasingly brighter than any other source with increasing z; *(iii)* compared to QSOs and galaxies the intrinsic afterglow spectrum is a featureless power law and thus easier to work with; *(iv)* finally, there is another aspect which plays in favor of GRBs and it is the fact that for standard afterglow light curves and spectra, the increase in the luminosity distance with z is compensated at least partially by the cosmic time stretching effect, meaning that the afterglow flux at a given observed time after the GRB trigger is not expected to fade signifi-

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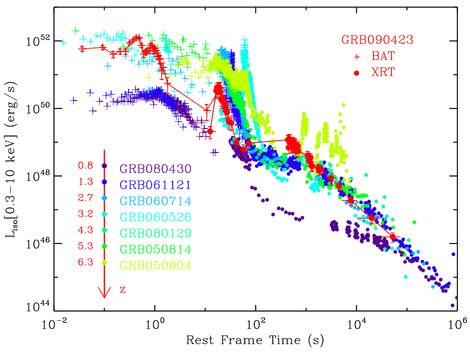

Fig. 1. Rest-frame γ-ray and X-ray light curves for bursts at different redshifts. Red data indicate the BAT and XRT light curves of GRB 090423 in the source rest-frame. For more details see Salvaterra et al. (2009).

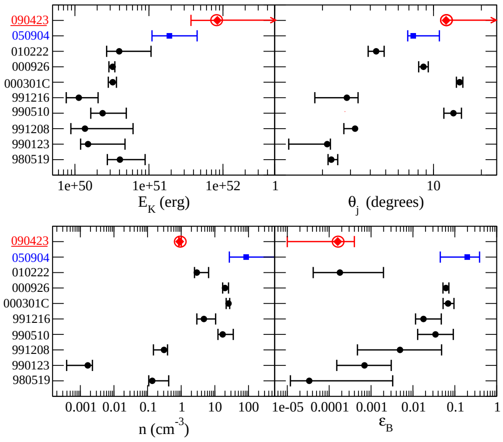

Fig. 2. Comparison of GRB 090423 best fit parameters with few moderate-z GRBs ($z \sim 1-3$) and with the high-z GRB 050904 ($z = 6.295$). For more details see Chandra et al. (2010).

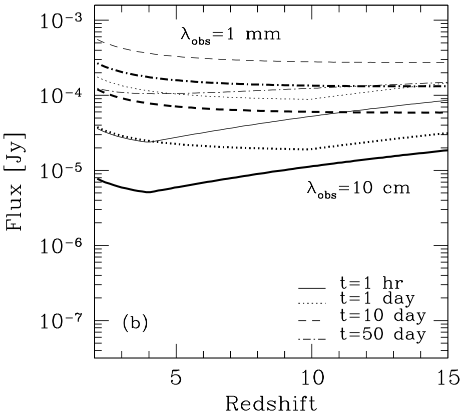

Fig. 3. Observed flux for a GRB hosted by a typical halo (having the mean mass) as a function of z. The curves refer to an observed frequency of 1 mm (thin lines) and 10 cm (thick lines) and for observed times after the GRBs of 1 hr (solid), 1 day (dotted), 10 day (dashed) and 50 day (dot-dashed). For more details see Ciardi & Loeb (2000).

cantly with increasing z, at least in the IR and radio range (e.g. Ciardi & Loeb 2000; Lamb & Reichart 2000). This latest point is exemplified in Figure 3.

In addition, Bloom et al. (2009) detected the first GRB bright enough to be seen with naked eye and which could have been easily detected in K-band with a meter-class telescope up to $z = 17$.

All this indicates that GRBs could be detected to even higher-z than already done. In the following I will discuss their possible use as probes of the high-z universe.

2. Probes of the high-z universe

If it is true that the physics driving GRBs from the first, metal free, massive stars is different than that governing GRBs from more standard stars as recent studies seem to suggest (see e.g. Komissarov & Barkov 2010; Mészáros & Rees 2010; Suwa & Ioka 2011), then their signatures (e.g. luminosity and duration) are expected to be different and they could be used to discriminate their progenitors.

Despite the GRB rate does not trace the star formation rate (SFR) in an unbiased way, with the due corrections it can be used to investigate the star formation history (e.g. Yuksel et al. 2008; Kistler et al. 2009; Butler, Bloom & Poznanski 2010), as shown in Figure 4, where the agreement with observations of Lyman Break Galaxies corrected for galaxies below the detection thresholds (upper set of triangles) suggests that the GRB estimate (red diamonds) incorporates the bulk of the high-z star forma-

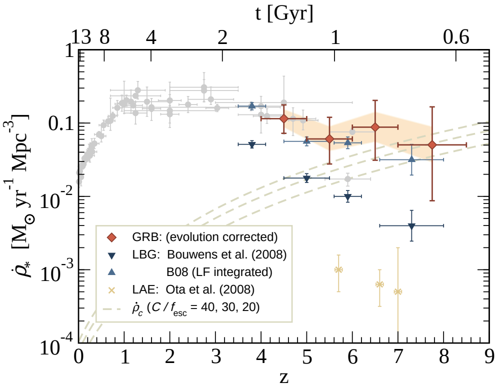

Fig. 4. The cosmic star formation history. Shown are the data compiled in Hopkins & Beacom (2006) (light circles) and contributions from Lyα Emitters from Ota et al. (2008). Recent Lyman Break Galaxies data is shown for two UV luminosity functions integrations: down to $0.2\,L^*_{z=3}$ (down triangles; as given in Bouwens et al. 2008) and complete (up triangles). The (bias-corrected) `Swift` GRB inferred rates are diamonds. Also shown is the critical SFR from Madau, Haardt & Rees (1999) for a clumping factor of $C/f_{\rm esc} = 40, 30, 20$ (dashed lines, top to bottom). For more details see Kistler et al. (2009).

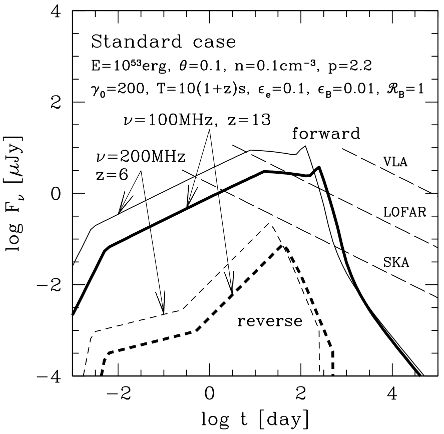

Fig. 5. GRB afterglow forward shock (solid line) and reverse shock (dashed line) fluxes, shown as a function of the observed time t at frequencies near the redshifted 21 cm radiation for two representative redshifts, $z = 6$ (thin lines) and 13 (thick), corresponding to an observed frequency of $\nu = 200$ MHz and 100 MHz, respectively. The model uses standard parameters for the GRB. The 5σ sensitivities of the `VLA`, `LOFAR` and `SKA` for integration times of one-third of t and band width $\Delta\nu = 50$ MHz are also shown by the long dashed lines. For more details see Ioka & Mészáros (2005).

tion down to the faint end of the luminosity function.

The spectra of GRBs can be used in analogy to those of QSOs to study the interstellar medium (ISM) and/or IGM. In particular, the absorption spectra of GRB 050904 has already been used to constrain HI at the end of the reionization process (Totani et al. 2006; Gallerani et al. 2007).

An intriguing possibility exists associated to the radio afterglow of GRBs. The interest in this frequency band has lately increased thanks to the radio interferometers which are being built (e.g. `LOFAR`, `MWA`, `PAPER`) or planned for the future (like the `SKA`). Among many other scientific applications, these telescopes will try to detect the redshifted 21 cm line associated to the hyperfine transition of the ground state of HI. In Figure 5 the GRB afterglow forward and reverse shock fluxes are shown as a function of the observed time at frequencies near the redshifted 21 cm radiation. While these fluxes should be detectable by the present and next generation of radio interferometers, if absorption lines are to be detected as well, then the flux should be larger than ~ 1 mJy$(0.002/\tau_{21cm})$, where τ_{21cm} is the HI optical depth (Ioka & Mészáros 2005). The conclusion is that it will be difficult to observe an absorption line, also with the `SKA`, except for very energetic sources. Thus, this could be a feasible observation for GRBs from the first stars. In fact, a similar calculation has been repeated more recently by Toma, Sakamoto & Mészáros (2011) for massive metal-free stars, finding that typically the flux at the same frequencies should be at least an order of magnitude higher than for a standard GRB.

While this would be an interesting possibility to probe the high-z IGM, Inoue, Omukai & Ciardi (2007) investigated the feasibility of detecting atomic and molecular absorption lines in the ISM. Figure 6 shows the spectra of

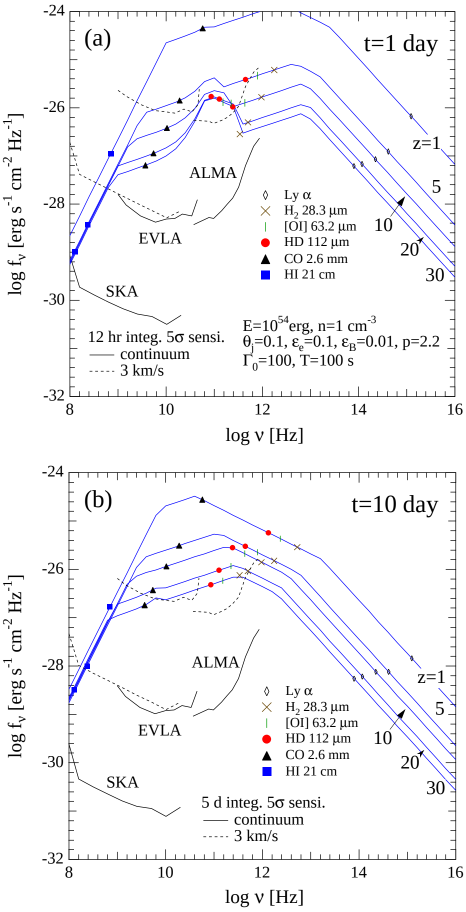

Fig. 6. Broadband spectra of GRB afterglows with fiducial parameters except for $E = 10^{54}$ erg, at different z as labelled and fixed post-burst observer time (a) $t = 1$ day and (b) 10 days. The redshifted frequencies for the lowest-lying transitions of H_2 (crosses), HD (circles), CO (triangles) and [OI] (vertical bars), as well as the Ly α (diamonds) and HI 21cm (squares) transitions are indicated on each spectra. Overlayed are 5 σ continuum and 3 km/s resolution spectroscopic sensitivities of various observational facilities, assuming integration times 50 % of t. For more details see Inoue, Omukai & Ciardi (2007).

GRBs afterglows at different z and observed time. The redshifted frequencies for some transitions of H2, HD, CO, OI, Lyα and 21 cm are indicated on each spectra, together with the 5σ sensitivities of a number of observational facilities. As in the case of the IGM, also this might turn out to be a feasible observation.

In conclusion, GRBs can be used in multiple ways to probe the high-z universe. In the following I will discuss up to which z we can expect to have GRBs and how many of them.

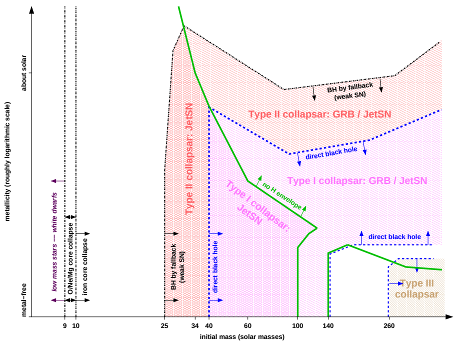

Fig. 7. Collapsar types resulting from single massive stars as a function of initial metallicity and initial mass. For more details see Heger et al. (2003).

3. High-z GRBs: how many?

The current understanding is that long GRBs (LGRBs) are associated to collapsars without their H envelope (e.g. Fryer 1999; Heger et al. 2003; Hirschi, Meynet & Maeder 2006). In Figure 7 by Heger et al. (2003) the collapsar range is shown as a function of the initial mass of the progenitor star and its metallicity. Any star lying above the no H envelope line can produce a GRB, with the exception of the Pair Instability Supernova range, where no black hole formation takes place. It has now been established that a first generation of metal-free stars (PopIII) pollutes the surroundings and induces a transition to PopII/I, more traditional stars once the gas metallicity has reached a critical value, Z_{crit} (e.g. Bromm et al. 2001; Schneider et al. 2002). It would thus seem that it were not possible to have GRBs from the very first stars because they would not be able to get rid of their H envelope. On the other hand, lately several authors (e.g. Komissarov & Barkov 2010; Mészáros & Rees 2010; Toma, Sakamoto & Mészáros 2011; Suwa & Ioka

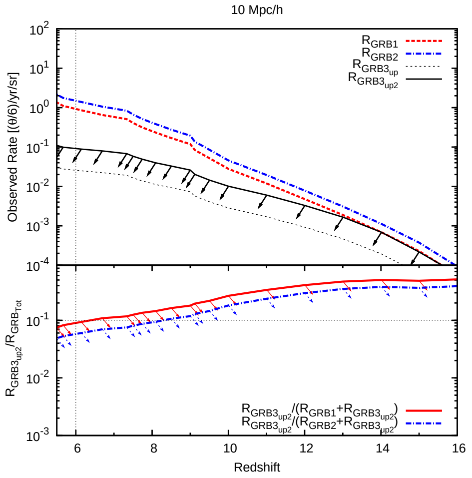

Fig. 8. *Upper panel:* Observed rate for GRBs in the simulation with side box of 10 Mpc h^{-1} comoving. Dashed-red lines represent the rate of GRB1, dashed-dotted-blue lines the rate of GRB2, the solid-dark lines are the upper limits for the rate of GRB3 and dotted lines are a more restrict upper limit for the same sample. *Bottom panel*: Evolution with redshift of the ratio between the expected rate of GRB3 and the total rate obtained summing the rate of the samples GRB3+GRB1 (upper solid-red line) and GRB3+GRB2 (lower dashed-dotted-blue line), for the three simulations with different size box. For more details see Campisi et al. (2011).

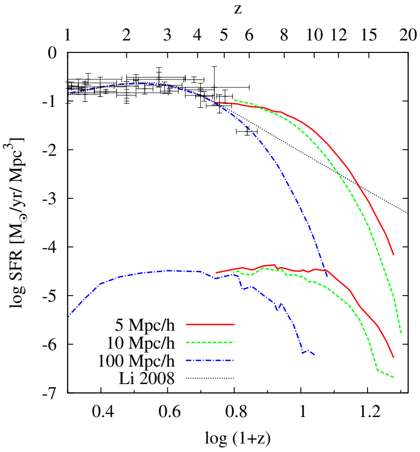

Fig. 9. Star formation rate density, SFR [$M_\odot$ yr^{-1} Mpc^{-3}], as a function of redshift for the simulation with comoving side box of 5 Mpc/h (red-solid line), 10 Mpc/h (green-dashed line) and 100 Mpc/h (blue-dotted-dashes line). For each of them, we show the total star formation rate density (upper lines) and the SFR of particles with $Z < Z_{crit}$ (PopIII SFRs). For more details see Campisi et al. (2011).

2011) have revisited the properties of the high mass end/low metallicity stars and found that a relativistic jet can potentially pierce the envelope of a PopIII star, indicating that from a theoretical point of view we expect to have GRBs from the dawn of star formation. How many GRBs do we expect to be originated at high-z, and which percentage of these could be associated to PopIII stars?

Because GRBs are associated to the final stages in the evolution of massive stars, it has been assumed that the GRB rate followed the SFR and this is a plausible assumption as long as the time delay between the formation of a massive star and a GRB event is short compared to the Hubble time. Under this assumption it has typically been found that ~ 10% of GRBs would come from $z > 5$ (this number is model dependent, but there is some agreement between different authors; see e.g. Wijers et al. 1998; Blain & Natarajan 2000; Ciardi & Loeb 2000; Lamb & Reichart 2000; Porciani & Madau 2001; Bromm & Loeb 2002; Natarajan et al. 2005; de Souza, Yoshida & Ioka 2011). It has then been realized that the number of high-z GRBs observed by `BATSE` and `Swift` is underestimated unless it is assumed either that there is an evolution of the luminosity function or that the rate of GRBs is enhanced in low metallicity environments ($Z < 0.2 - 0.3\ Z_\odot$) or a combination of the two (e.g. Salvaterra & Chincarini 2007; Salvaterra et al. 2007, 2009; Campisi et al. 2010). In particular, it was found that only 0.0004 GRBs as GRB 090423 should have been seen in 4 yrs of `Swift` operations, an inconsistency which can be solved if one or both of the above points are taken into account (Salvaterra et al. 2009).

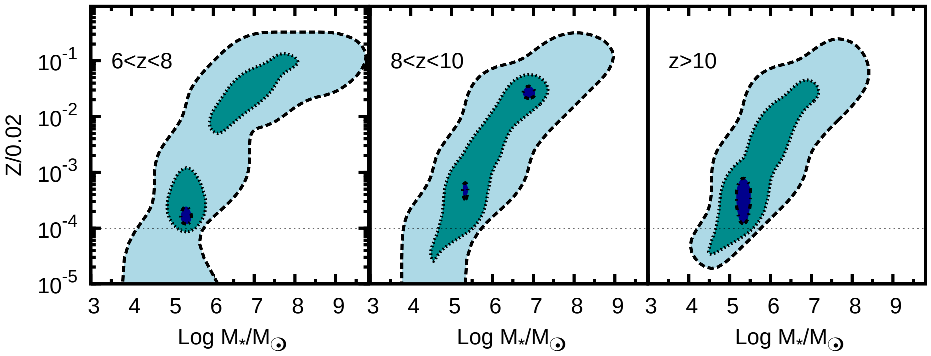

Fig. 10. Probability of having a GRB3 in a host galaxy with given stellar mass and metallicity, in three different redshift bins. The contours refer to a probability of 100%, 75% and 25%, where the percentages refer to the contours from the outermost to the innermost, respectively. The horizontal line indicates the critical metallicity Z_{crit}.

4. GRBs from primordial stars

We have established that GRBs can originate from metal-free or extremely metal poor first stars, so it is important to estimate how many such GRBs we expect. The first attempt to quantify the PopIII vs PopII/I contribution to the GRB rate was done by Bromm & Loeb (2002) with a semi-analytic approach which took into account the SFR of the two populations. Recently, Campisi et al. (2011) have revisited this estimate by means of hydrodynamical simulations. Following the paradigm that a transition from PopIII to PopII stars occurs when a metallicity threshold, Z_{crit}, has been reached, Maio et al. (2010) have run hydrodynamical simulations which include all the relevant primordial chemistry, star formation, feedback effects and the transition in the star formation mode mentioned above. The simulations were run in different box sizes (5, 10 and 100 comoving Mpc h^{-1}) to compare results to observations (which are more numerous at low z, requiring large simulation boxes), and at the same time to investigate the high-z universe (which requires higher resolution achievable only with smaller boxes).

The resulting SFR is shown in Figure 9. The upper set of curves refer to the total SFR, while the lower set to the contribution from PopIII stars. PopIII star continue forming down to the lowest simulated redshift, although their contribution to the SFR is always very small.

From the SFR we have derived the observed cumulative rate of GRBs (refer to the original paper for details of the calculations), shown in Figure 8 for the 10 Mpc h^{-1} box with $Z_{crit} = 10^{-4}$ Z$_\odot$ as a reference.

The lines refer to the rate from the GRB1 (red), GRB2 (blue) and GRB3 (black) populations which have been selected according to the following metallicity cut: GRB1 are obtained selecting star particles with $Z > Z_{crit}$, i.e. it includes all the PopII/I stars; GRB2 only those star particles with $Z_{crit} < Z < 0.5$ Z$_\odot$ (consistently with some observations of GRBs suggesting that they might preferentially reside in low metallicity environments) and GRB3 include only star particles with $Z < Z_{crit}$. The lower panels indicate the contribution of GRBs from PopIII stars to the total rate. The rate of GRB1 and 2 is very similar, while the rate of GRB3 is much smaller, although it becomes more important as redshift increases, as expected. The GRB3 is a firm upper limit, based on the assumption that no LGRBs associated with a PopIII star has been detected by `Swift`. At $z > 6$ the total expected rate is ~ 1, while the number decreases to 0.02 for GRB3, which is consistent with both current theoretical and observational estimates. The probability of a GRB to be associated to a PopIII star is below 20% at $z > 8$, but is becomes as large as 40-50% at higher redshift.

Figure 10 shows the characteristics of the galaxies which host GRBs from PopIII stars in different redshift bins, in terms of the probability of having a GRB from a PopIII star in a host galaxy of a given stellar mass and metallicity. Regardless of redshift, they seem to be associated with objects of stellar masses 10^5 $M_\odot$ (although this is somewhat resolution dependent) and metal poor, but not below the critical value. This because the metallicity of a galaxy is averaged over the whole object, but it can host pockets of metal free gas.

5. Conclusion

The main conclusions can be summarized as follows:

- GRBs have been spectroscopically observed up to $z \sim 8$, but could be detected from even higher redshift;
- they are expected to form since the dawn of the star formation process;
- GRBs can be great probes of e.g. the star formation history, the interstellar and intergalactic medium, and are potentially far better probes than high-z quasars and galaxies;
- as z increases, the probability of a GRB to be associated to a PopIII star increases as well ($< 20\%$ at $z > 8$ and up to 40-50%).

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